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Evidence for Light Scalar Resonances in Charm Meson Decays from Fermilab E791

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Abstract

From Dalitz-plot analyses of $D^+ \to \pi^-\pi^+\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays, we find evidence for light and broad scalar resonances $\sigma(500)$ and $\kappa(800)$. From a Dalitz-plot analysis of $D_s^+ \to \pi^-\pi^+\pi^+$ decays, we measure the masses and decay widths of the scalar resonances $f_0(980)$ and $f_0(1370)$.

1 Introduction

The constituent quark model of QCD provides a successful description of pseudo-scalar and vector mesons, which can be conveniently arranged into $SU(3)_c$ nonet representations. One also expects a corresponding scalar meson nonet to exist, and much experimental effort has been directed towards identifying its members. The following states have been identified thus far, listed by isospin:

- $I=0$: $f_0(600)$ or $\sigma(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
- $I=1/2$: $\kappa(800)$, $K_0^*(1430)$
- $I=1$: $a_0(980)$, $a_0(1450)$

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Scalar mesons have traditionally been studied via scattering experiments. However, in these experiments the mesons can be difficult to disentangle from nonresonant background due to their broad widths and lack of a distinctive angular distribution. Thus, some scalar states are controversial ($\sigma(500)$ and $\kappa(800)$), while others have only poorly-determined parameters ($f_0(980)$, $a_0(980)$, and $f_0(1370)$).

Recently, large samples of $D^+_{(s)} \to \pi^-\pi^+\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays have been used to study scalar mesons (S) via the quasi-two-body decay $D^+ \to S\pi^+,\ S \to h^-\pi^+$ (charge-conjugate modes are assumed unless noted otherwise). The scalar masses and decay widths are determined by fitting a Dalitz-plot distribution to the square of coherently-summed decay amplitudes $|\sum_n \mathcal{A}(D \to S_n\pi)|^2$. In this paper, we present such results from Fermilab E791. This experiment produced D mesons using a 500 GeV/c π^- beam incident on C and Pt targets. The subsequent D decays were reconstructed using a silicon-strip vertex detector, a large-aperture spectrometer, and various particle identification detectors. Details of the experiment can be found in Ref. [1].

2 Dalitz-Plot Formalism

The analyses select $D^+_{(s)} \to \pi^-\pi^+\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays by requiring that there be a 3-track vertex well-separated from the primary interaction vertex. Pions and kaons are identified using information from two threshold Čerenkov counters. The $D^+ \to K^-\pi^+\pi^+$ sample contains 15090 events with about 6% background, while the $D^+ \to \pi^-\pi^+\pi^+$ and $D^+_s \to \pi^-\pi^+\pi^+$ samples contain 1686 and 937 events, respectively, with about 30% background. The $K\pi\pi$ sample is significantly larger and has a lower level of background because it is Cabibbo-favored.

To study the resonance structure of each sample, an unbinned maximum likelihood fit is performed. The likelihood function is $\mathcal{L} = \prod_{events}[\mathcal{P}_S + \mathcal{P}_B]$, where $\mathcal{P}_S$ is the probability density function (pdf) for signal and $\mathcal{P}_B$ is the pdf for background. The latter pdf is obtained from a fit to events in mass sidebands or from Monte Carlo simulation. The signal pdf is $\mathcal{P}_S = (1/N_S)\, g(M)\, \varepsilon(m^2_{12}, m^2_{13})\, |\mathcal{A}|^2$, where N_S is a normalization factor, $g(M)$ describes the signal shape in the $\pi\pi\pi$ or $K\pi\pi$ mass spectrum, and $\varepsilon(m^2_{12}, m^2_{13})$ is the acceptance over the Dalitz plot, including smearing. The amplitude $\mathcal{A}$ is the coherent sum of a uniform non-resonant (NR) amplitude and amplitudes of resonances:

$$\mathcal{A} = a_0 e^{i\delta_0}\mathcal{A}_0 + \sum_{n=1}^{N} a_n e^{i\delta_n}\mathcal{A}_n(m^2_{12}, m^2_{13})\,. \quad (1)$$

The coefficients a_n and relative phases δ_n are determined from the fit. The amplitude $\mathcal{A}_n = F_D^{(J)} F_n^{(J)} \mathcal{M}_n^{(J)} BW_n$, where $F_D^{(J)}$ and $F_n^{(J)}$ are Blatt-Weisskopf factors that depend on the spin (J) and radii (r_D and r_R) of the parent D and intermediate resonance; $\mathcal{M}_n^{(J)}$ is the angular-momentum-conserving factor $(-2)^J p^J q^J P_J(\cos\theta)$, where $\vec{p}$, $\vec{q}$ are the momenta of the D and one of the daughters of the intermediate resonance in the resonance rest frame, and $\cos\theta = \hat{p}\cdot\hat{q}$; and BW_n is the relativistic Breit-Wigner propagator $\left[m_n^2 - m^2 - i m_n \Gamma_n(m)\right]^{-1}$, where m is the invariant mass of the track pair forming a resonance (m_{12} or m_{13}), m_n is the resonance mass, and $\Gamma_n(m)$ is the mass-dependent width. More details of these expressions can be found in Ref. [2]. Finally, each resonant amplitude is Bose-symmetrized with respect to the identical pions: $\mathcal{A}_n = \mathcal{A}_n[(\mathbf{12})\mathbf{3}] + \mathcal{A}_n[(\mathbf{13})\mathbf{2}]$.

3 Results

The results of the likelihood fits are given in Tables 1–3. The tables list the coefficients a_n and phases δ_n resulting from the fits, along with the decay fraction for each amplitude. The decay fraction for an amplitude is defined as its intensity integrated over the Dalitz plot, divided by the integrated intensity of all amplitudes coherently summed. To assess the quality of the fit, a fast Monte Carlo program was developed that produces binned Dalitz-plot densities according to signal and background pdfs, including detector smearing effects. The difference between this density distribution and that of the data – summed over all bins – is taken as the χ^2 of the fit. The number of bins is the number of degrees of freedom.

Table 1 gives the results for $D^+ \to \pi^-\pi^+\pi^+$. The left-most column lists results obtained when fitting to established resonances, while the right-most column lists results obtained when an additional scalar resonance is included. For the latter fit, the χ^2 per degree of freedom (ν) is significantly improved, and the non-resonant fraction constitutes a much smaller component of the total width (in the left-most column it dominates). The mass and width obtained by the fit for the additional resonance (denoted "σ") are $m = 478^{+24}_{-23} \pm 17$ MeV/c^2 and $\Gamma = 324^{+42}_{-40} \pm 21$ MeV/c^2. As a test we also fit the data with vector, tensor, and toy (Breit-Wigner with no phase variation) models for the additional amplitude. In all cases we obtain a higher χ^2/ν than that obtained with the additional scalar amplitude.

Table 2 gives the results for $D_s^+ \to \pi^-\pi^+\pi^+$. The left-most column lists results obtained when fitting to established resonances, while the other two columns list results obtained when the $\rho^0(770)$ and $\rho^0(1450)$

are excluded. The parameters determined from the fit are the mass and width of the $f^0(1370)$, and the mass and coefficients g_π, g_K of a coupled-channel Breit-Wigner width [3] for the $f^0(980)$. The results are $m_{f_0(1370)} = 1434 \pm 18 \pm 9$ MeV/c^2, $\Gamma_{f_0(1370)} = 172 \pm 32 \pm 6$ MeV/c^2, and $m_{f_0(980)} = 977 \pm 3 \pm 2$ MeV/c^2, $g_\pi = 0.09 \pm 0.01 \pm 0.01$, $g_K = 0.02 \pm 0.04 \pm 0.03$. We also fit the data using the same Breit-Wigner for the $f_0(980)$ as that used for the other resonances; the resulting fit is nearly as good and the decay fractions and phases are essentially unchanged.

Table 3 gives the results for $D^+ \to K^-\pi^+\pi^+$. The left-most column lists results when fitting only to established resonances and fixing the parameters of the scalar $K_0^*(1430)$. The middle column lists results obtained when the $K_0^*(1430)$ parameters are allowed to float, and, in addition, Gaussian form factors $F_D \cdot F_R = \exp(-p^2 r_D^2/12) \cdot \exp(-p^2 r_R^2/12)$ are used for the $K_0^*(1430)$ to account for the size of the decaying mesons. The meson radii r_D and r_R (also appearing in Blatt-Weisskopf factors) are now determined from the fit. The right-most column lists results when an additional scalar resonance is included (also with Gaussian form factors in its amplitude). This last fit yields a significantly improved χ^2/ν, and the NR fraction is reduced from about 90% to 13%, which is more consistent with expectations. The mass and width of the additional resonance (denoted "κ") are $m = 797 \pm 19 \pm 43$ MeV/c^2 and $\Gamma = 410 \pm 43 \pm 87$ MeV/c^2. Including this additional resonance, the fit obtains $K_0^*(1430)$ parameters $m_{K^*(1430)} = 1459 \pm 7 \pm 5$ MeV/c^2 and $\Gamma_{K^*(1430)} = 175 \pm 12 \pm 12$ MeV/c^2; these values are shifted by $+47$ MeV and -119 MeV, respectively, with respect to PDG values [5]. The meson radii are $r_D = 5.0 \pm 0.5$ GeV^{-1} and $r_R = 1.6 \pm 1.3$ GeV^{-1}. We also fit the data with vector, tensor, and toy (Breit-Wigner with no phase variation) models for the additional amplitude; in all cases we obtain a higher χ^2/ν than that obtained with the κ amplitude.

In summary, we have performed Dalitz-plot analyses for the decays $D^+ \to \pi^-\pi^+\pi^+$, $D_s^+ \to \pi^-\pi^+\pi^+$, and $D^+ \to K^-\pi^+\pi^+$. For the first sample, including an additional scalar resonance with mass near 500 MeV/c^2 significantly improves the quality of the fit. For the $D^+ \to K^-\pi^+\pi^+$ sample, including a scalar resonance with mass near 800 MeV/c^2 improves the quality of the fit. When this resonance is included, the fit obtains a mass and width for the $K_0^*(1430)$ that are shifted with respect to PDG values.

References

[1] E. M. Aitala *et al.*, *Eur. Phys. J Direct* **C4**, 1 (1999).

	Estab. Resonances	**Adding $\sigma(500)$**
	Fraction (%) Phase	Fraction (%) Phase
NR	38.6 ± 9.7 $(150 \pm 12)^\circ$	$7.8 \pm 6.0 \pm 2.7$ $(57.3 \pm 19.5 \pm 5.7)^\circ$
$\sigma\,\pi^+$	– –	$46.3 \pm 9.0 \pm 2.1$ $(206 \pm 8.0 \pm 5.2)^\circ$
$\rho^0(770)\pi^+$	20.8 ± 2.4 0° (fixed)	$33.6 \pm 3.2 \pm 2.2$ 0° (fixed)
$f_0(980)\pi^+$	7.4 ± 1.4 $(152 \pm 16)^\circ$	$6.2 \pm 1.3 \pm 0.4$ $(165 \pm 11 \pm 3.4)^\circ$
$f_2(1270)\pi^+$	6.3 ± 1.9 $(103 \pm 16)^\circ$	$19.4 \pm 2.5 \pm 0.4$ $(57.3 \pm 7.5 \pm 2.9)^\circ$
$f_0(1370)\pi^+$	10.7 ± 3.1 $(143 \pm 9.7)^\circ$	$2.3 \pm 1.5 \pm 0.8$ $(105 \pm 18 \pm 0.6)^\circ$
$\rho^0(1450)\pi^+$	22.6 ± 3.7 $(46 \pm 15)^\circ$	$0.7 \pm 0.7 \pm 0.3$ $(319 \pm 39 \pm 11)^\circ$
χ^2/ν	254/162	138/162

Table 1: Results of the maximum likelihood fit to the $D^+ \to \pi^-\pi^+\pi^+$ Dalitz plot (from Ref. [2]).

	Estab. Resonances	**No $\rho^0(770)$**	**No $\rho^0(1450)$**
	Fraction (%) Magnitude Phase	Fraction (%) Magnitude Phase	Fraction (%) Magnitude Phase
NR	$0.5 \pm 1.4 \pm 1.7$ $0.09 \pm 0.14 \pm 0.04$ $(181 \pm 94 \pm 51)^\circ$	7.5 ± 4.8 0.36 ± 0.12 $(165 \pm 23)^\circ$	5.0 ± 3.8 0.30 ± 0.12 $(149 \pm 25)^\circ$
$f_0(980)\pi^+$	$56.5 \pm 4.3 \pm 4.7$ 1 (fixed) 0° (fixed)	58.0 ± 4.9 1 (fixed) 0° (fixed)	54.1 ± 4.0 1 (fixed) 0° (fixed)
$\rho^0(770)\pi^+$	$5.8 \pm 2.3 \pm 3.7$ $0.32 \pm 0.07 \pm 0.19$ $(109 \pm 24 \pm 5)^\circ$	– – –	11.1 ± 2.5 0.45 ± 0.06 $(81 \pm 15)^\circ$
$f_2(1270)\pi^+$	$19.7 \pm 3.3 \pm 0.6$ $0.59 \pm 0.06 \pm 0.02$ $(133 \pm 13 \pm 28)^\circ$	22.2 ± 3.3 0.62 ± 0.06 $(109 \pm 11)^\circ$	20.8 ± 3.0 0.62 ± 0.05 $(124 \pm 11)^\circ$
$f_0(1370)\pi^+$	$32.4 \pm 7.7 \pm 1.9$ $0.76 \pm 0.11 \pm 0.03$ $(198 \pm 19 \pm 27)^\circ$	30.4 ± 6.9 0.72 ± 0.11 $(156 \pm 19)^\circ$	34.7 ± 7.2 0.80 ± 0.11 $(159 \pm 14)^\circ$
$\rho^0(1450)\pi^+$	$4.4 \pm 2.1 \pm 0.2$ $0.28 \pm 0.07 \pm 0.01$ $(162 \pm 26 \pm 17)^\circ$	5.8 ± 2.2 0.32 ± 0.06 $(144 \pm 20)^\circ$	– – –
χ^2/ν	72/68	93/68	104/68

Table 2: Results of the maximum likelihood fit to the $D_s^+ \to \pi^-\pi^+\pi^+$ Dalitz plot (from Ref. [3]).

	Estab. Resonances	**Floating $K_0^*(1430)$ with Gaussian form factors**	**Adding $\kappa(800)$**
	Fraction (%) Magnitude Phase	Fraction (%) Magnitude Phase	Fraction (%) Magnitude Phase
NR	90.9 ± 2.6 1.0 (fixed) $0°$(fixed)	89.5 ± 16.1 2.72 ± 0.55 $(-49 \pm 3)°$	$13.0 \pm 5.8 \pm 4.4$ $1.03 \pm 0.30 \pm 0.16$ $(-11 \pm 14 \pm 8)°$
$\kappa\,\pi^+$	– – –	– – –	$47.8 \pm 12.1 \pm 5.3$ $1.97 \pm 0.35 \pm 0.11$ $(187 \pm 8 \pm 18)°$
$\bar{K}^*(892)\pi^+$	13.8 ± 0.5 0.39 ± 0.01 $(54 \pm 2)°$	12.1 ± 3.3 1.0 (fixed) $0°$ (fixed)	$12.3 \pm 1.0 \pm 0.9$ 1.0 (fixed) $0°$ (fixed)
$\bar{K}_0^*(1430)\pi^+$	30.6 ± 1.6 0.58 ± 0.01 $(54 \pm 2)°$	28.7 ± 10.2 1.54 ± 0.75 $(6 \pm 12)°$	$12.5 \pm 1.4 \pm 0.5$ $1.01 \pm 0.10 \pm 0.08$ $(48 \pm 7 \pm 10)°$
$\bar{K}_2^*(1430)\pi^+$	0.4 ± 0.1 0.07 ± 0.01 $(33 \pm 8)°$	0.5 ± 0.3 0.21 ± 0.18 $(-3 \pm 26)°$	$0.5 \pm 0.1 \pm 0.2$ $0.20 \pm 0.05 \pm 0.04$ $(-54 \pm 8 \pm 7)°$
$\bar{K}^*(1680)\pi^+$	3.2 ± 0.3 0.19 ± 0.01 $(66 \pm 3)°$	3.7 ± 1.9 0.56 ± 0.48 $(36 \pm 25)°$	$2.5 \pm 0.7 \pm 0.3$ $0.45 \pm 0.16 \pm 0.02$ $(28 \pm 13 \pm 15)°$
χ^2/ν	167/63	126/63	46/63

Table 3: Results of the maximum likelihood fit to the $D^+ \to K^-\pi^+\pi^+$ Dalitz plot (from Ref. [4]).

[2] E. M. Aitala *et al.*, *Phys. Rev. Lett.* **86**, 770 (2001).

[3] E. M. Aitala *et al.*, *Phys. Rev. Lett.* **86**, 765 (2001).

[4] E. M. Aitala *et al.*, *Phys. Rev. Lett.* **89**, 121801 (2002).

[5] K. Hagiwara *et al.*, *Phys. Rev. D* **66**, 1 (2002). See also note [15] of Ref. [4].